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Capture and collection of lampreys: the state of the science

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Abstract The need for native lamprey conservation, improved lamprey fishery management, and better assessment of non-indigenous lamprey control measures has resulted in increased effort to survey lamprey populations and assess their status. Depending on the study objectives and target species/life stage, collection methods vary dramatically. We therefore provide a comprehensive review of sampling considerations and techniques used to capture, collect, handle, and enumerate both juvenile and adult lamprey life stages. Surveys for lamprey are often constrained by the lack of basic biological information, such as reliable characters for field identification of larvae (ammocoetes), migratory timing of anadromous forms, and spawning/nest building behavior of adults. However, there are a number of studies that have documented habitat preferences of the relatively sedentary ammocoetes. Consequently, existing sampling protocols have focused on the development of stratified sampling that targets optimal ammocoete habitat. In addition to this approach, we discuss methods and gear that can be used to survey migratory life stages, lamprey nests, and difficult-to-sample, deepwater ammocoete habitats.

Keywords Lampetra · Petromyzontiformes · Gear · Sampling · Handling · Anesthetic

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Introduction

Development of accurate methods for assessing lamprey status is critically needed to manage lamprey fisheries, conserve endangered/threatened lamprey stocks, and assess the efficacy of control measures. Lampreys have historically supported economically and culturally important fisheries worldwide. In many English and Finnish rivers, lampreys are still taken in commercial fisheries, despite dramatic declines in abundance (Tuunainen et al. 1980; Valtonen 1980; Masters et al. 2006). In northwestern North America, lamprey continue to be important to indigenous peoples, even though declines in abundance have limited the use of lamprey for food, medicinal, and ceremonial purposes (Close et al. 2002, 2004).

Over half of all lamprey species are considered to be endangered, vulnerable, or extinct in at least a portion of their range (Renaud 1997). Declines in native lamprey abundance have resulted primarily from habitat degradation or reduction, and poisoning to control non-native lamprey

(Vladykov 1973; Renaud 1997; Filcek et al. 2005). The need for lamprey conservation has resulted in calls for standardized sampling methods to assess lamprey status (Kirchhofer 1995; Moser and Close 2003; Harvey and Cowx 2003). Much of the methodology currently in use for capture and collection of lamprey was originally developed in the 1950s during efforts to enumerate and eradicate non-indigenous sea lamprey *Petromyzon marinus* in the North American Great Lakes (Braem and Ebel 1961). Sea lamprey became established in the Great Lakes in the early 1900s, and their proliferation resulted in the development of methods to assess abundance and evaluate the effects of various control measures (reviewed in Christie and Goddard 2003; Slade et al. 2003).

The unique life history of lampreys presents both challenges and opportunities for capture and collection. Adult lamprey typically spawn in gravel/cobble substrate, building a discrete nest in which the eggs are laid (Fig. 1). After hatching, the larvae (ammocoetes) settle in silt/sand substrate, where they assume a largely sedentary lifestyle. The degree to which ammocoetes move during this life stage, which may last 3–7 years, is not well documented. However, some ammocoetes clearly make both downstream and upstream excursions, occupying new habitat as a result of either active or passive displacement (Potter 1980a; Maitland 2003; White and Harvey 2003; Quintella et al. 2004).

Fig. 1 Pacific lamprey *Lampetra tridentata* construct a discrete nest using 20–40 mm substrate. It covers an average area of 0.1–0.2 m^2 and is excavated to a mean depth of 5–10 cm. *Photo courtesy of the US Fish and Wildlife Service*

Of the 38 recognized lamprey species, 18 feed parasitically as adults and may participate in extensive anadromous or potamodromous migrations (Potter and Gill 2003). The parasitic forms metamorphose (becoming macrophthalmia), emigrate from freshwater nursery areas, are parasitic for 1–2 years, and then participate in free-swimming, spawning migrations. In contrast, the non-parasitic species do not range far from their natal habitat. Because all lampreys exhibit protracted freshwater residence as larvae and are typically more concentrated in freshwater streams as adults, lamprey capture and collection has targeted sedentary ammocoetes, emigrating macrophthalmia, and migrating adults mainly in freshwater rivers and streams.

A number of techniques are currently used to capture, collect, and enumerate various lamprey species and life stages. Moreover, several independent protocols for sampling lamprey have been developed (Harvey and Cowx 2003; Slade et al. 2003). Collection methods vary dramatically depending on the objective of sampling, the target species, and/or the life stage of interest. Our objective is to provide a comprehensive review of techniques that have worked in a variety of settings that provides guidance for future survey development and refinement of existing protocols.

Considerations for sampling design

Much of the available data on lamprey distribution and abundance has been collected during surveys for other fish species. Consequently, the timing of collections, gear efficiency, and site selection have not been ideally suited to assessing lamprey status (Heard 1966; Bond et al. 1983; Todd and Kelso 1993). However, modification of existing surveys to provide useful lamprey information is possible, and this may often be the only recourse for obtaining lamprey data (Harvey and Cowx 2003).

As is the case for any fish survey, the appropriate sampling design for lamprey is dependent upon the objective of the survey: documentation

of presence/absence, enumeration (density, absolute or relative abundance), or population dynamics (size distributions, trends in abundance over time). However, development of appropriate sampling designs for lamprey can be complicated by two factors: species identification of ammocoetes, and lack of basic biological information.

Distinguishing ammocoetes of closely related species can be extremely difficult (Heard 1966; Brown and Moyle 1993; Gardiner 2003; Maitland 2003; Filcek et al. 2005; Meeuwig and Bayer 2005; Fig. 2). Non-parasitic and parasitic species pairs (Potter 1980b) or satellite species (Vladykov and Kott 1980) co-occur in many river systems. Often, members of paired and satellite species are not even genetically distinguishable (Docker et al. 1999). Due to unreliable species identification techniques, researchers have resorted to holding specimens until metamorphosis (Heard 1966; Beamish 1980), conducting post-hoc genetic or morphological identification (Filcek et al. 2005; Meeuwig and Bayer 2005), or sampling only above impassable obstacles, where anadromous parasitic forms do not occur (Maitland 2003).

The lack of basic life history information can also be a factor in sampling design. For example, the timing of macrophthalmia emigration or the degree of movement by ammocoetes must be established before accurate reach-specific estimates of population growth or mortality can be made. Similarly, identification of preferred habitat is needed to develop ammocoete sampling programs, while information on the incidence of multiple nest building or occupation of a single nest by multiple spawners is needed to interpret the results of nest surveys (Jang and Lucas 2005; Mundahl and Sagan 2005; Stone and Brandt 2005; Stone In press).

Fig. 2 There are no reliable keys to distinguish many larval lamprey species. For example, adult Pacific lamprey *L. tridentata* and western brook lamprey *L. richardsoni* ammocoetes co-occur and are difficult to distinguish in the field. *Photo courtesy of the Confederated Tribes of the Umatilla Indian Reservation*

Selection of sampling locations

Juveniles

The first step in assessing ammocoete abundance is to classify and quantify habitat within the study area. Ammocoetes are patchily distributed in freshwater streams and rivers. A number of studies have focused on defining ammocoete habitat preferences by assessing the relative effects of environmental variables on ammocoete abundance: water depth and velocity; light levels; substrate grain size, depth, and organic content; and chlorophyll levels (reviewed in Hardisty and Potter 1971a; Ojutkangas et al. 1995). In these studies, habitats are randomly sampled, and all environmental variables are measured. The relative importance of each variable to lamprey abundance is then quantified statistically (e.g., Malmqvist 1980; Potter et al. 1986; Young et al. 1990; Beamish and Jebbink 1994; Beamish and Lowartz 1996; Jellyman and Glova 2002; Torgeson and Close 2004; Stone and Brandt 2005).

In most studies that have defined optimal ammocoete habitat on small spatial scales, substrate grain size and water velocity were the most important indicators of larval lamprey abundance (Malmqvist 1980; Beamish and Jebbink 1994; Beamish and Lowartz 1996; Almeida and Quintella 2002; Sugiyama and Goto 2002). However, other variables, such as water depth, proximity to adult spawning areas, and riparian canopy can be important on larger spatial scales (Almeida and Quintella 2002; Torgeson and Close 2004). In addition, the relative importance of habitat variables can change with ammocoete size (Young et al. 1990; Almeida and Quintella 2002; Sugiyama and Goto 2002).

After defining the characteristics of optimal ammocoete habitat, sampling areas are classified

into broad categories. For example, in tributaries of the Great Lakes, habitat suitability in sea lamprey surveys is qualitatively assessed as preferred (Type I = a loosely compacted mixture of sand and fine organic matter in depositional areas), acceptable (Type II = shifting sand or gravel with little fine organic matter), or unacceptable (Type III = bedrock, rubble or gravel) (Mullett and Bergstedt 2003; Slade et al. 2003). Harvey and Cowx (2003) recommend delineation of habitat as either optimal (stable, fine sediment or sand >15 cm deep, low water velocity with organic detritus present) or sub-optimal (transient shallow sediment interspersed with coarse substrate such as sediment trapped by tree roots, detritus overlying bedrock, or submerged vegetation rooted in silt or sand).

Following classification of habitats, ammocoete abundance in the optimal habitat is estimated by multiplying the observed density in samples from optimal habitat by the amount of optimal habitat. The degree to which sub-optimal habitats are sampled varies depending on the objectives, scope, and funding available for the survey. In some cases, only optimal habitat is sampled to reduce costs (Slade et al. 2003). Total ammocoete abundance is obtained by assuming that larval density and variance of sub-optimal habitat are in constant proportion to that of optimal habitat (Slade et al. 2003). However, Hansen et al. (2003) found that larval density varies substantially in sub-optimal habitats, and that a fixed-ratio model produced inaccurate estimates of ammocoete abundance in streams with large amounts of sub-optimal habitat. Consequently, sampling of both optimal and sub-optimal habitats is recommended (Harvey and Cowx 2003; Hansen et al. 2003).

Adults

Lamprey nests or spawning adults can be enumerated; however such surveys are often fraught with difficulties. Lamprey construct nests in gravel and cobble substrates similar to those of salmonids (Hardisty and Potter 1971b; Takayama 2002; Fig. 1). As with salmonid redd surveys, mapping lamprey nests requires adequate water depth and clarity, as well as prior knowledge of preferred habitat types and spawning times (Takayama 2002; Jang and Lucas 2005; Stone In press). Enumeration of nests to produce estimates of adult abundance is problematic in that multiple adults may participate in nest building, or a single adult may build more than one nest (Farlinger and Beamish 1984; Jang and Lucas 2005; Mundahl and Sagan 2005). Moreover, mixed species aggregations of spawning lamprey have also been documented (Cochran and Pettinelli 1988; Cochran and Gripentrog 1992). Nevertheless, nest surveys can be used to identify likely ammocoete rearing areas (Torgeson and Close 2004), evaluate changes in quality and quantity of spawning habitat (Cochran and Gripentrog 1992; Takayama 2002; Jang and Lucas 2005; Mundahl and Sagan 2005), and assess populations with very low abundance or recruitment (Farlinger and Beamish 1984).

Trapping and visual observations of migrating adult lamprey have been used as an index of abundance in a variety of systems (e.g., Beamish 1980; Schuldt and Heinrich 1982; Stier and Kynard 1986a; Cochran and Marks 1995; Moser and Close 2003; Mullet et al. 2003). For this type of sampling, site selection was limited to areas where adults are concentrated during spawning migrations, typically at man-made barriers such as dams or weirs. Development of appropriate survey methodology and accurate interpretation of the results require some prior knowledge of migration times, environmental effects on movement, and specific lamprey behaviors (Moser and Close 2003).

Sampling frequency and timing

Juveniles

Ammocoete populations are sampled annually in most surveys (e.g., Weise and Pajos 1998; Quintella et al. 2003; Slade et al. 2003). This infrequent sampling arises from the assumption that ammocoetes do not move much between rearing areas in a given year. This is thought to be the case particularly for non-anadromous forms or populations that settle in very low gradient streams (Potter 1980a). However, a recent

mark-recapture study of ammocoetes in their native range indicated that lamprey ammocoetes readily move both upstream and downstream, and that they traveled up to 27 m during a 7-week period (Quintella et al. 2004). Another consideration is the degree of temporal variation in the amount of optimal habitat. In tributaries of the Great Lakes, the proportion of optimal habitat (Type I) showed no significant interannual variation, but the amount of sub-optimal habitat (Type II) varied significantly among years (Slade et al. 2003). Therefore, more frequent sampling may be required to accurately document reach-specific population dynamics (i.e., recruitment, growth, metamorphosis, or mortality rates).

The seasonal timing of ammocoete surveys should allow for collection of all size classes of interest. Although sampling for small ammocoetes (<40 mm) is less efficient than for larger size classes (Pajos and Weise 1994), the presence of age-0 lamprey is important in surveys where evidence of recent recruitment is desired (Moser and Close 2003; Harvey and Cowx 2003). Such surveys should occur only in the summer or fall after larval settlement. For anadromous species in most systems, sampling in late summer and fall also allows for collection of metamorphosing lamprey prior to their emigration from freshwater habitats (Harvey and Cowx 2003; Slade et al. 2003).

Larval lamprey surveys typically use electrofishers in either single pass (e.g., Malmqvist 1980; Potter et al. 1986; Slade et al. 2003; Almeida and Quintella 2002) or depletion sampling (consecutive samples collected at the same location; e.g., Pajos and Weise 1994; Beamish and Lowartz 1996; Harvey and Cowx 2003; Jellyman and Glova 2002; Torgeson and Close 2004; Stone and Brandt 2005). For depletion sampling, Pajos and Weise (1994) electrofished 1–2 m wide transects every 15 min until no additional lamprey were collected, while Harvey and Cowx (2003) recommended a 5-min resting period when electrofishing a 1-m^2 quadrat. Extended intervals between repeated electrofishing sessions may be necessary to offset the effects of narcosis on ammocoetes buried in the sediment (Pajos and Weise 1994).

Adults

While relatively infrequent sampling for ammocoetes can produce a reliable snapshot of lamprey abundance in a given location, repeated sampling is required for migrating adults to account for seasonal, daily, or even hourly variation in run timing. Timing of the adult lamprey spawning migration is dictated by a variety of environmental cues: temperature, discharge, photoperiod, and presence of olfactory cues (Hardisty and Potter 1971b; Bjerselius et al. 2000; Moser et al. 2005). The temporal variability in these environmental cues will dictate adult lamprey sampling intervals. In some cases, nearly continuous sampling throughout a protracted migration period is needed to produce reliable estimates of adult lamprey abundance (Stier and Kynard 1986a; Moser and Close 2003; Mullett et al. 2003).

Spawning ground surveys generally occur over a shorter time period; however, the timing of such surveys is critical. The peak of spawning activity may last less than one week and can end abruptly (Cochran and Pettinelli 1988). In addition, nests may only be visible for little over one month following their initial construction (Stone In press). Ideally, surveys of lamprey nests should be conducted soon after spawning, when the nest material is cleanest and most easily identified. In most systems, spawning occurs in spring or early summer. Due to funding constraints, lamprey nest surveys are often added to salmonid redd surveys. Unfortunately, the timing of these surveys may be either before or after the peak of lamprey spawning activity.

Active capture techniques

Juveniles

Most juvenile lamprey surveys rely on the use of a backpack or shore-based electrofisher in waters less than 0.8 m deep (Fig. 3). Sampling often involves a two-stage method, such as that detailed by Weisser and Klar (1990). First, 90–125 V direct current with a 10–25% duty cycle is applied at a slow rate of 3 pulses/s to induce ammocoetes to emerge from the sediment. A pattern of three

Fig. 3 Backpack electroshocking is one of the most common methods for assessing larval lamprey abundance. A typical first step in developing the sampling design is to identify and quantify optimal larval rearing habitat. *Photo courtesy of the Confederated Tribes of the Umatilla Indian Reservation*

slow pulses followed by a skipped pulse (3:1 pulse pattern) also helps to encourage emergence. Second, immediately after the ammocoetes emerge, a fast pulse setting of 30 pulses/s is used to immobilize them (Slade et al. 2003). Extended exposure to electrofishing can result in electronarcosis of buried ammocoetes and failure to emerge (Pajos and Weise 1994). Moreover, lamprey size and density, as well as water depth, temperature, and conductivity, all affect capture efficiency (Bowen et al. 2003; Steeves et al. 2003). Consequently, capture efficiencies of various electrofishers and personnel should be tested under a range of field conditions prior to development of standardized sampling protocols (Steeves et al. 2003).

While electrofishing in shallow water relies on capture of ammocoetes in dip nets or seines, electrofishing in deep water is often coupled with either a suction pump or trawl to bring immobilized larvae to the surface (McLain and Dahl 1968; Bergstedt and Genovese 1994; Fodale et al. 2003). Bergstedt and Genovese (1994) tested the capture efficiency of a deepwater electrofisher in water depths of 1–2 m. Power for this device was supplied by a standard backpack electrofisher. Immobilized larvae were suctioned from the sediment surface via a 7.6-cm hose and passed into a collection basket without going through the suction pump. Larvae were alive and unharmed following collection. Overall capture efficiency was 75%, but it decreased with increasing larval lamprey length. The efficiency of this device has not been determined in areas with significant current velocity (R. Reed, Karuk Tribal Fisheries Program, personal communication). The Wisconsin Department of Natural Resources personnel electrofish with multiple cabled electrodes from several boats. A large crew of people dipnet the stunned lamprey, thereby allowing greater coverage of large streams (P. Cochran, Saint Mary's University, personal communication). Validated methods for collecting ammocoetes in deep water are desperately needed, as recent research indicates that some of the highest ammocoete densities can occur in 5–7 th order reaches, where water depths exceed 1 m (S. van de Wetering, Siletz Indians, personal communication.).

A variety of other active gear types have been employed to collect ammocoetes. These include use of a shovel or suction dredge to remove lamprey from the sediment (Kainua and Valtonen 1980; Beamish and Youson 1987; Ojutkangas et al. 1995) or towed nets to collect both migrating ammocoetes and macrophthalmia (Heard 1966; Beamish and Youson 1987; Beamish and Levings 1991; Gadomski and Barfoot 1998). Lee and Weise (1989) used a manned submersible to visually quantify lamprey in deep lentic habitats. They also determined ammocoete abundance via surface collection of dead and dying lamprey that had been exposed to a larvicide. Finally, Quintella et al. (2004), described the detection of ammocoetes tagged with passive integrated transponder (PIT) tags in waters less than 1 m deep using a portable PIT-detection system. While labor intensive, this method allows for documentation of fine-scale movement patterns and microhabitat use without handling the lamprey (Quintella et al. 2004).

Adults

Adult lamprey, particularly resident forms, are regularly captured in electrofishing surveys designed to sample other fish species. Consequently, this is an important technique for documentation of lamprey occurrence, and much of the historical data on lamprey distribution is based on electrofishing survey data. Adult lampreys are vagile and

exhibit cryptic behaviors, hiding under boulders or other structures (Cochran and Gripentrog 1992; Kelso and Glova 1993). Due to low capture efficiency, electrofishing for adult lampreys does not provide accurate abundance estimates.

As is the case for eel (*Anguilla* sp.; Tesch 2003), almost every known fishing technique has been used to collect either adult lamprey or hosts with attached lamprey. These include jigging (Beamish and Levings 1991), use of towed nets and seines (Pletcher 1963; Beamish 1980; Bond et al. 1983), dip netting, and collection by hand (Heard 1966; Cochran 1987, 1989; Close et al. 2004). Parasitic-phase adults can be obtained via opportunistic capture in commercial and recreational fishing operations that target host species (Johnson and Anderson 1980; Cochran et al. 2003a, b; Cochran and Lyons 2004). Finally, visual counts of lamprey nests and spawning aggregations can yield valuable data on spawning habitat, timing of spawning events, and relative abundance (Cochran and Gripentrog 1992; Takayama 2002; Jang and Lucas 2005; Stone In press).

Passive gear

Juveniles

A variety of passive gear types have been employed to capture migrating ammocoetes or macrophthalmia. Low capture efficiency renders these gear types of limited use for abundance estimation, but they can be important tools for determining the presence of upstream spawning or rearing areas, timing of juvenile migration, or relative abundance among sites or years. Gear types include rotary screw traps (Fig. 4), floating inclined plane traps (Beamish and Levings 1991), anchored nets (Heard 1966; Long 1968; Johnston 1997; Gadomski and Barfoot 1998; White and Harvey 2003), and rotating cooling water intake screens at power stations (Claridge et al. 1986).

Adults

For migrating adults, passive gear types are often more successful than active collection methods, both for research and in fisheries. Trap designs

Fig. 4 Rotary screw traps used to collect emigrating salmonid smolts can be used to collect juvenile lamprey and provide information on the distribution of spawning and rearing areas. *Photo by James P. Reed*

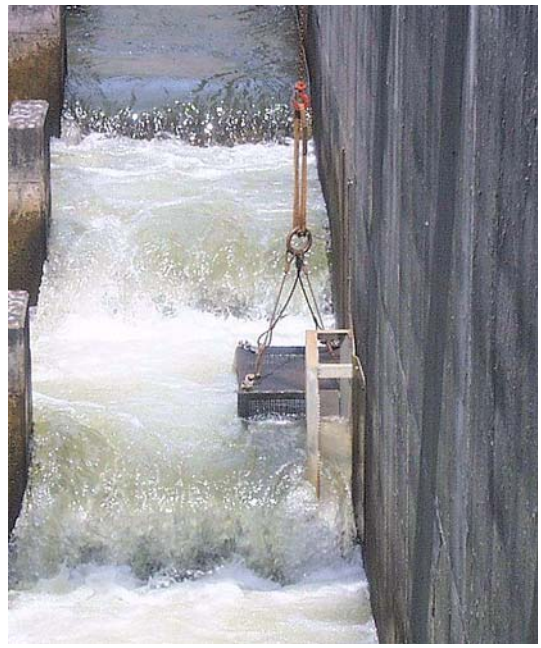

Fig. 5 A lamprey trap installed in a fishway is used to capture adult lamprey as they pass over a weir at Bonneville Dam, Columbia River, USA. *Photo courtesy of the National Marine Fisheries Service*

vary, but they are typically set at obstacles to upstream passage or in dam fishways, where adult lamprey are concentrated (e.g., Beamish 1980; Schuldt and Heinrich 1982; Stier and Kynard 1986a; Cochran and Marks 1995; Moser and Close 2003; Mullett et al. 2003; Cochran and Lyons 2004; Fig. 5). As is the case for eels (*Anguilla* sp.;

Fig. 6 A simple lamprey pot allows collection of adult lamprey during the spawning migration in Cedar Creek, a tributary of the Lewis River in Washington State. *Photo courtesy of the US Fish and Wildlife Service*

Tesch 2003), a broad range of passive gear has also been used in unobstructed streams and rivers to capture adult lamprey (Smith and Elliott 1953; Morris and Maitland 1987; Beamish and Levings 1991; Kelso and Glova 1993; Masters et al. 2006; Jang and Lucas 2005, Fig. 6). In most cases, passive gear is used in short-term, mark-recapture studies and to obtain specimens for research (Smith and Elliott 1953; Beamish 1980; Beamish and Levings 1991; Bergstedt and Seelye 1995; Moser and Close 2003; Masters et al. 2006; Jang and Lucas 2005) or in fisheries (Tuunainen et al. 1980; Valtonen 1980; Sjoberg 1980). However, long-term adult trapping efforts in the Great Lakes have been used to develop estimates of lamprey abundance and survival (Bergstedt et al. 2003; Mullett et al. 2003).

Passive gear has also been used successfully to collect parasitic- and spawning phase lamprey. In most cases, parasitic-phase lamprey are captured incidentally during trapping or pound netting operations for host species (Johnson and Anderson 1980; Cochran and Marks 1995; Harvey 2001). However, baiting traps with potential hosts has also been used to collect lamprey when they are abundant and attachment rates are high (Hall 1963). Use of a sex pheromone to draw spawning-phase lamprey into traps has also been used with some success (Johnson et al. 2006).

Visual enumeration of adult lamprey passage has traditionally been conducted at dam count stations (Stier and Kynard 1986a; Haro and Kynard 1997; Moser and Close 2003). While this method can provide a useful index of abundance, it is labor-intensive and prone to error. Migrating adult lamprey are primarily nocturnal. Consequently, counts taken during the day at many facilities will underestimate adult lamprey passage. In addition, lamprey can pass via uncounted routes, mill back and forth in front of count stations, and fall back over dams (Haro and Kynard 1997; Moser and Close 2003). These behaviors can cause both over- and underestimation of lamprey passage. Therefore, dam counts should be used with caution when assessing lamprey status (Moser and Close 2003).

Handling considerations

Adult and juvenile lamprey are notoriously active and difficult to handle without anesthesia. Nonetheless, to save time, many lamprey surveys do not anesthetize for enumeration and measurement. A V-shaped measuring trough or curved pipe fitted with a ruler is useful for controlling lamprey during measurement (Harvey and Cowx 2003). In instances where species identification is difficult, use of magnifiers and a white background for examination of ammocoetes can be very helpful (Harvey and Cowx 2003; Gardiner 2003). While lamprey are hardy and can be subjected to extended holding without significant mortality, they are also quite susceptible to physical injury. This is particularly true of juveniles, where loss of mucous can result in subsequent fungal infection, particularly in warm water temperature (Mueller et al. 2006; C. Schreck, U. S. Geological Survey, Oregon Cooperative Fish and Wildlife Research Unit, Oregon State University, personal communication). Therefore, every effort should be made to reduce mucous loss and physical trauma during handling.

Anesthesia is recommended for the more extensive handling associated with tagging, very accurate determinations of length, or meristic measurements for species identification. A wide variety of anesthetics have been used with success. Tricaine methanesulfonate (MS222) has

been widely used at concentrations of 30–70 ppm (e.g., Stier and Kynard 1986b; Weise and Pajos 1998; Moser and Close 2003). Quintella et al. (2004) used 1 ml l^{-1} 2-phenoxyethanol with no mortality of ammocoetes and transforming juveniles. Ethyl 3-aminobenzoate (Benzocaine) at 50 mg l^{-1} is also recommended, although care must be taken to avoid deep anesthesia that can result in an overly slow recovery period (Harvey and Cowx 2003). Eugenol (clove oil, 60 ppm) is recommended for adult lamprey due to the rapid recovery period and apparent lack of effects on orientation. Regardless of the anesthetic used, lamprey should be allowed to recover fully prior to release. Before release, juveniles are often held in a bucket with sediment until all cohorts have recovered enough to burrow into the substrate (C. Claire, Idaho Department of Fish and Game, personal communication).

Conclusions

Several protocols have been developed for long-term assessment of lamprey for both conservation (Harvey and Cowx 2003) and eradication (Slade et al. 2003). These protocols provide useful guidelines for development of ammocoete sampling programs using an electrofisher in waters <0.8 m in depth. In addition, Harvey and Cowx (2003) provide sample data sheets and estimates of person-days required to conduct the work. Continuing steps toward refinement of survey protocols are (1) testing for sampling bias (e.g., Steeves et al. 2003), (2) modeling to illuminate survey changes that can reduce sampling effort without loss of statistical power (e.g., Hansen et al. 2003; Slade et al. 2003), and (3) developing sampling methods for new species and habitats (e.g., Fodale et al. 2003). Many native lampreys have recently been identified as species of concern for conservation. Moreover, continued assessment for control of non-indigenous lampreys and any future invasions is needed (Balon et al. 1986; Farlinger and Beamish 1984; Christie and Goddard 2003). Therefore, the demand for information to help develop lamprey sampling protocols in all parts of the world is likely to increase in the coming years.

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References

Almeida PR, Quintella BR (2002) Larval habitat of the sea lamprey (*Petromyzon marinus*) in the River Mondego (Portugal). In: Collares-Pereira MJ, Coelho MM, Cowx IG (eds) Freshwater fish conservation: options for the future. Fishing News Books, Blackwell Science, Oxford, pp 212–130

Balon EK, Crawford SS, Lelek A (1986) Fish communities of the upper Danube River (Germany, Austria) prior to the new Rhein-Main-Donau connection. Environ Biol Fishes 15:243–271

Beamish FWH, Jebbink JA (1994) Abundance of lamprey larvae and physical habitat. Environ Biol Fishes 39:209–214

Beamish FWH, Lowartz S (1996) Larval habitat of American brook lamprey. Can J Fish Aquat Sci 53:693–700

Beamish RJ (1980) Adult biology of the river lamprey (*Lampetra ayresi*) and the Pacific lamprey (*Lampetra tridentata*) from the Pacific Coast of Canada. Can J Fish Aquat Sci 37:1906–1923

Beamish RJ, Levings CD (1991) Abundance and freshwater migrations of the anadromous parasitic lamprey (*Lampetra tridentata*), in a tributary of the Fraser River, British Columbia. Can J Fish Aquat Sci 48:1250–1263

Beamish RJ, Youson JH (1987) Life history and abundance of young adult *Lampetra ayresi* in the Fraser River and their possible impact on salmon and herring stocks in the Strait of Georgia. Can J Fish Aquat Sci 44:525–537

Bergstedt RA, Genovese JH (1994) New technique for sampling sea lamprey larvae in deepwater habitats. N Am J Fish Manage 14:449–452

Bergstedt RA, McDonald RB, Mullett KM, Wright GM, Swink WD, Burnham KP (2003) Mark-recapture population estimates of parasitic sea lampreys (*Petromyzon marinus*) in Lake Huron. J Great Lakes Res 29:226–239

Bergstedt RA, Seelye JG (1995) Evidence for lack of homing by sea lampreys. Trans Am Fish Soc 124:235–239

Bjerselius R, Li W, Teeter JH, Seelye JG, Johnsen PB, Maniak PJ, Grant GC, Polkinghorne CN, Sorensen PW (2000) Direct behavioral evidence that unique bile acids released by larval sea lamprey (*Petromyzon*

marinus) function as a migratory pheromone. Can J Fish Aquat Sci 57:557–569
Bond CE, Kan TT, Myers KW (1983) Notes on the marine life of the river lamprey, *Lampetra ayresi*, in Yaquina Bay, Oregon and the Columbia River estuary. Fish Bull 81:165–167
Bowen AK, Weisser JW, Bergstedt RA, Famoye F (2003) Response of larval sea lampreys (*Petromyzon marinus*) to pulsed DC electrical stimuli in laboratory experiments. J Great Lakes Res 29:174–182
Braem RA, Ebel WJ (1961) A back-pack shocker for collecting lamprey ammocoetes. Prog Fish Cult 23:87–91
Brown LR, Moyle PB (1993) Distribution, ecology, and status of the fishes of the San Joaquin River drainage, California. Calif Fish Game 79:96–114
Christie GC, Goddard CJ (2003) Sea Lamprey International Symposium (SLIS II): advances in the integrated management of sea lamprey in the Great Lakes. J Great Lakes Res 29:1–14
Claridge PN, Potter IC, Hardisty MW (1986) Seasonal changes in movements, abundance, size composition, and diversity of the fish fauna of the Severn Estuary. J Mar Biol Assoc UK 66:229–258
Close DA, Fitzpatrick MS, Li HW (2002) The ecological and cultural importance of a species at risk of extinction, Pacific lamprey. Fisheries 27:19–25
Close DA, Jackson AD, Conner BP, Li HW (2004) Traditional ecological knowledge of Pacific lamprey (*Entosphenus tridentatus*) in northeastern Oregon and southeastern Washington from indigenous peoples of the Confederated Tribes of the Umatilla Indian Reservation. J Northwest Anthropol 38:141–161
Cochran PA (1987) The southern brook lamprey (*Icthyomyzon gagei*) in the St. Croix River drainage of Wisconsin and Minnesota. Copeia 1987:443–446
Cochran PA (1989) Maintaining parasitic lampreys in closed laboratory systems. Am Biol Teacher 51:115–119
Cochran PA, Gripentrog AP (1992) Aggregation and spawning by lampreys (genus *Ichthyomyzon*) beneath cover. Environ Biol Fishes 33:381-387
Cochran PA, Hodgson JY, Kinziger AP (2003a) Change in energy density of the sea lamprey (*Petromyzon marinus*) during its parasitic phase: implications for modeling food consumption and growth. J Great Lakes Res 29:297–306
Cochran PA, Lyons J (2004) Field and laboratory observations on the ecology and behavior of the silver lamprey (*Ichthyomyzon unicuspis*) in Wisconsin. J Freshwater Ecol 19:245–253
Cochran PA, Lyons J, Gehl MR (2003b) Parasitic attachments by overwintering silver lampreys, *Ichthyomyzon unicuspis*, and chestnut lampreys *Ichthyomyzon castaneus*. Env Biol Fish 68:65–71
Cochran PA, Marks JE (1995) Biology of the silver lamprey, *Ichthyomyzon unicuspis*, in Green Bay and the lower Fox River, with a comparison to the sea lamprey, *Petromyzon marinus*. Copeia 1995:409–421
Cochran PA, Pettinelli TC (1988) Northern and southern brook lampreys (*Ichthyomyzon fossor* and *I. gagei*) in Minnesota. J Minn Acad Sci 54:23–27
Docker MF, Youson JH, Beamish RJ, Devlin R (1999) Phylogeny of the lamprey genus *Lampetra* inferred from mitochondrial cytochrome *b* and ND3 gene sequences. Can J Fish Aquat Sci 56:2340–2349
Farlinger SP, Beamish RJ (1984) Recent colonization of a major salmon producing lake in British Columbia by Pacific lamprey (*Lampetra tridentata*). Can J Fish Aquat Sci 41:278–285
Filcek KB, Gilmore SA, Scribner KT, Jones ML (2005) Discriminating lamprey species using multilocus microsatellite genotypes. N Am J Fish Manage 25:502–509
Fodale MF, Bronte CR, Bergstedt RA, Cuddy DW, Adams JV (2003) Classification of lentic habitat for sea lamprey (*Petromyzon marinus*) larvae using a remote seabed classification device. J Great Lakes Res 29:190–203
Gadomski DM, Barfoot CA (1998) Diel and distributional abundance patterns of fish embryos and larvae in the lower Columbia and Deschutes rivers. Environ Biol Fishes 51:353–368
Gardiner R (2003) Identifying lamprey: a field key for sea, river, and brook lamprey. In: Conserving Natura 2000 Rivers. Conservation Techniques Series No. 4 English Nature, Peterborough. Available via the Life In UK Rivers project, http://www.english-nature.org.uk/lifeinukrivers/publications/lamprey_key.pdf, Cited 22 March 2006
Hall JD (1963) An ecological study of the chestnut lamprey, *Ichthyomyzon castaneus* (Girard), in the Manistee River, Michigan. PhD Thesis, University of Michigan, Ann Arbor, MI 101 pp
Hansen MJ, Adams JV, Cuddy DW, Richards JM, Fodale MF, Larson GL, Ollila DJ, Slade JW, Steeves TB, Young RJ, Zerrenner A (2003) Optimizing larval assessment to support sea lamprey control in the Great Lakes. J Great Lakes Res 29:766–782
Hardisty MW, Potter IC (1971a) The behaviour, ecology, and growth of larval lampreys. In: Hardisty MW, Potter IC (eds) The biology of lampreys, vol 1. Academic Press, London, pp 85–125
Hardisty MW, Potter IC (1971b) The general biology of adult lampreys. In: Hardisty MW, Potter IC (eds) The biology of lampreys, vol 1. Academic Press, London, pp 249–277
Haro A, Kynard B (1997) Video evaluation of passage efficiency of American shad and sea lamprey in a modified Ice Harbor fishway. N Am J Fish Manage 17:981–987
Harvey CJ (2001) A stable isotope analysis of food web structure in Lake Superior. PhD Thesis, University of Wisconsin, Madison, 137 pp
Harvey J, Cowx I (2003) Monitoring the river, brook, and sea lamprey, *Lampetra fluviatilis*, *L. planeri*, and *Petromyzon marinus*. In: Conserving Natura 2000 Rivers. Conservation Techniques Series No. 5 English Nature, Peterborough. Available via the Life In UK Rivers project, http://www.english-nature.org.uk/ lifeinukrivers/publications/lamprey_monitoring.pdf. Cited 23 March 2006
Heard WR (1966) Observations on lampreys in the Naknek River system of southwest Alaska. Copeia 1966:332–339

Jang M-H, Lucas MC (2005) Reproductive ecology of the river lamprey. J Fish Biol 66:499–512

Jellyman DJ, Glova GJ (2002) Habitat use by juvenile lampreys (*Geotria australis*) in a large New Zealand river. NZ J Mar Freshwater Res 36:503–510

Johnson BGH, Anderson WC (1980) Predatory-phase sea lamprey (*Petromyzon marinus*) in the Great Lakes. Can J Fish Aquat Sci 37:2007–2020

Johnson NS, Luehring MA, Siefkes MJ, Li W (2006) Mating pheromone reception and induced behavior in ovulating female sea lamprey. N Am J Fish Manage 26:88–96

Johnston TA (1997) Downstream movements of young-of-the-year fishes in Catamaran Brook and the Little Southwest Miramichi River, New Brunswick. J Fish Biol 51:1047–1062

Kainua K, Valtonen T (1980) Distribution and abundance of European river lamprey (*Lampetra fluviatilis*) larvae in three rivers running into Bothnian Bay, Finland. Can J Fish Aquat Sci 37:1960–1966

Kelso JRM, Glova GJ (1993) Distribution, upstream migration and habitat selection of maturing lampreys, *Geotria australis*, in Pigeon Bay Stream, New Zealand. Australian J Mar Freshwater Res 44:749–759

Kirchhofer A (1995) Concept of conservation for the European brook lamprey (*Lampetra planeri*) in Switzerland. Fischokologie 8:93–108

Lee DS, Weise JG (1989) Habitat selection of lentic larval lampreys: preliminary analysis based on research with a manned submersible. J Great Lakes Res 15:156–163

Long C (1968) Diel movement and vertical distribution of juvenile anadromous fish in turbine intakes. Fish Bull 66:599–609

Maitland PS (2003) Ecology of the river, brook, and sea lamprey. In: Conserving Natura 2000 Rivers. Conservation Techniques Series No. 5 English Nature, Peterborough. Available via the Life in UK rivers project, http://www.english-nature.org.uk/lifeinukrivers/publications/lamprey.pdf . Cited 23 March 2006

Malmqvist B (1980) Habitat selection of larval brook lampreys (*Lampetra planeri*, Bloch) in a south Swedish stream. Oecologia 45:35–38

Masters JEG, Jang M-H, Ha K, Bird PD, Frear PA, Lucas MC (2006) The commerical exploitation of a protected anadromous species, the river lamprey (*Lampetra fluviatilis* (L.)), in the tidal River Ouse, northeast England. Aquat Conserv Mar Freshw Ecosyst 16:77–92

McLain AL, Dahl FM (1968) An electric beam trawl for the capture of larval lampreys. Trans Am Fish Soc 97:289–293

Meeuwig HM, Bayer JM (2005) Morphology and aging precision of statoliths from larvae of Columbia River Basin lampreys. N Am J Fish Manage 25:38–48

Morris KH, Maitland PS (1987) A trap for catching adult lampreys (Petromyzonidae) in running water. J Fish Biol 31:513–516

Moser M.L., Close D.A. (2003) Assessing Pacific lamprey status in the Columbia River Basin. Northwest Sci 77:116–125

Moser ML, Zabel RW, Burke BJ, Stuehrenberg LC, Bjornn TC (2005) Factors affecting adult Pacific lamprey passage rates at hydropower dams: using ''time-to-event'' analysis of radiotelemetry data. In: Spedicato MT, Marmulla G, Lembo G (eds) Aquatic telemetry: advances and applications. FAO-COISPA, Rome, pp 61–70

Mueller RP, Moursund RA, Bleich MD (2006) Tagging juvenile Pacific lamprey with passive integrated transponders: methodology, short-term mortality, and influence on swimming performance. N Am J Fish Manage 26:361–366

Mullett KM, Bergstedt RA (2003) Agreement among observers classifying larval sea lamprey (*Petromyzon marinus*) habitat. J Great Lakes Res 29:183–189

Mullett KM, Heinrich JW, Adams JV, Young RJ, Henson MP, McDonald RB, Fodale MF (2003) Estimating lake-wide abundance of spawning-phase sea lampreys (*Petromyzon marinus*) in the Great Lakes: extrapolating from sampled streams using regression models. J Great Lakes Res 29:240–252

Mundahl ND, Sagan RA (2005) Spawning ecology of the American brook lamprey, *Lampetra appendix*. Env Biol Fish 73:283–292

Ojutkangas E, Aronen K, Laukkanen E (1995) Distribution and abundance of river lamprey (*Lampetra fluviatilis*) ammocoetes in the regulated River Perhonjoki. Regul Rivers Res Manage 10:239–245

Pajos TA, Weise JG (1994) Estimating populations of larval sea lamprey with electroshocking sampling methods. N Am J Fish Manage 14:580–587

Pletcher FT (1963) The life history and distribution of lampreys in the Salmon and certain other rivers in British Columbia, Canada. MS thesis, University of British Columbia

Potter IC (1980a) Ecology of larval and metamorphosing lampreys. Can J Fish Aquat Sci 37:641–1657

Potter IC (1980b) The Petromyzoniformes with particular reference to paired species. Can J Fish Aquat Sci 37:595–1615

Potter IC, Gill HS (2003) Adaptive radiation of lampreys. J Great Lakes Res 29:95–112

Potter IC, Hilliard RW, Bradley JS, McKay RJ (1986) The influence of environmental variables on the density of larval lampreys in different seasons. Oecologia 70:433–440

Quintella BR, Andrade NO, Almeida PR (2003) Distribution, larval stage duration and growth of the sea lamprey ammocoetes, *Petromyzon marinus* L., in a highly modified river basin. Ecol Freshw Fish 12:286–293

Quintella BR, Andrade NO, Espanhol R, Almeida PR (2004) The use of PIT telemetry to study movements of ammocoetes and metamorphosing sea lampreys in river beds. J Fish Biol 65:1–10

Renaud CB (1997) Conservation status of Northern Hemisphere lampreys (Petromyzontidae). J Appl Ichthyol 13:143–148

Schuldt RJ, Heinrich JW (1982) Portable trap for collecting adult sea lampreys. Prog Fish-Cult 44:220–221

Sjoberg K (1980) Ecology of the European river lamprey (*Lampetra fluviatilis*) in northern Sweden. Can J Fish Aquat Sci 37:1974–1980

Slade JW, Adams JV, Cuddy DW, Neave FB, Sullivan WP, Young RJ, Fodale MF, Jones ML (2003) Techniques and methods for estimating abundance of larval and metamorphosed sea lampreys in Great Lakes tributaries, 1995–2001. J Great Lakes Res 29:130–136

Smith BR, Elliott OR (1953) Movement of parasitic-phase sea lampreys in lakes Huron and Michigan. Trans Am Fish Soc 82:123–128

Steeves TB, Slade JW, Fodale MF, Cuddy DW, Jones ML (2003) Effectiveness of using backpack electroshocking gear for collecting sea lamprey (*Petromyzon marinus*) larvae in Great Lakes tributaries. J Great Lakes Res 29:161–173

Stier K, Kynard B(1986a) Abundance, size, and sex ratio of adult sea-run sea lampreys, *Petromyzon marinus*, in the Connecticut River. Fish Bull 84:476–480

Stier K, Kynard B (1986b) Movement of sea-run sea lampreys, *Petromyzon marinus*, during the spawning migration in the Connecticut River. Fish Bull 84:749–753

Stone J (In press) Observations of nest characteristics, spawning habitat, and spawning behavior of Pacific and western book lamprey in a Washington stream. NW Sci

Stone J, Brandt S (2005) Spatial distribution and habitat use of Pacific lamprey (*Lampetra tridentata*) ammocoetes in a Western Washington stream. J Freshwater Res 20:171–185

Sugiyama H, Goto A (2002) Habitat selection by larvae of a fluvial lamprey, *Lethenteron reissneri*, in a small stream and an experimental aquarium. Ichthyol Res 49:62–68

Takayama M (2002) Spawning activities and physical characteristics of the spawning ground of *Lethenteron reissneri* at the headstream of the Himekawa River, central Japan. Ichthyol Res 49:165–170

Tesch F-W (2003) The eel. Blackwell Science, Ltd., Oxford, 408 pp

Todd PR, Kelso JRM (1993) Distribution, growth and transformation timing of larval Geotria australis in New Zealand. Ecol Freshwater Fish 2:99–107

Torgeson CE, Close DA (2004) Influence of habitat heterogeneity on the distribution of larval Pacific lamprey (*Lampetra tridentata*) at two spatial scales. Freshw Biol 49:614–630

Tuunainen P, Ikonen E, Auvinen H (1980) Lampreys and lamprey fisheries in Finland. Can J Fish Aquat Sci 37:1953–1959

Valtonen T (1980) European river lamprey (*Lampetra fluviatilis*) fishing and lamprey populations in some rivers running into Bothnian Bay, Finland. Can J Fish Aquat Sci 37:1967–1973

Vladykov VD (1973) North American nonparasitic lampreys of the family Petromyzonidae must be protected. Can Field-Nat 87:235–239

Vladykov VD, Kott E (1980) Description and key to metamorphosed specimens and ammocoetes of Petromyzonidae found in the Great Lakes Region. Can J Fish Aquat Sci 37:1616–1625

Weise JG, Pajos TA (1998) Intraspecific competition between larval sea lamprey year-classes as Salem Creek was recolonized, 1990–1994, after a lampricide application. N Am J Fish Manage 18:561–568

Weisser JW, Klar GT (1990) Electric fishing for sea lamprey (*Petromyzon marinus*) in the Great Lakes Region of North America. In: Cowx IG (ed) Developments in electric fishing. Fishing News Books, Oxford, pp 59–64

White JL, Harvey BC (2003) Basin-scale patterns in the drift of embryonic and larval fishes and lamprey ammocoetes in two coastal rivers. Env Biol Fishes 67:369–378

Young RJ, Kelso JRM, Weise JG (1990) Occurrence, relative abundance, and size of landlocked sea lamprey (*Petromyzon marinus*) ammocoetes in relation to stream characteristics in the Great Lakes. Can J Fish Aquat Sci 47:773–778